Development and application of geobotanical remote sensing methods for mineral exploration in thick vegetation areas(Abstract_要旨)

AUTHOR(S):

Arie, Naftali Hawu Hede

京都大学	博士（　　工　　学）	氏名	Arie Naftali Hawu Hede
論文題目	Development and application of geobotanical remote sensing methods for mineral exploration in thick vegetation areas（高植被率域における鉱物資源探査を目的とした地植物リモートセンシング法の開発と応用）		

In the 21st century, the world has experienced a rapid increase in the consumption and demand for mineral resources, which has resulted in considerable needs for innovation of natural resource exploration technologies. Remote sensing is one of the useful exploration techniques that has been commonly used in the prospecting phase, because it can provide a rapid assessment at low costs and with the minimal risks. However, as for the spectral applications, the applicability of remote sensing is limited to arid and semi-arid areas where vegetation is sparse or absent. Exploration and potential assessments of mineral deposits by optical remote sensing are difficult in thickly vegetated areas because the reflectance spectra of the vegetation conceal the spectra of the underlying soils and rocks. To overcome this constraint, the use of geobotanical remote sensing (GBRS) is promising. Based on those background, this study was aimed to develop GBRS methods for detecting the vegetation anomalies induced by the metal stress around mineral deposits and also to improve an image enhancement method for solving a problem of spectral mixture. Contents of each chapter can be summarized as follows.

Chapter 1 is an introduction that denotes the academic and social background of this study, the general notion of GBRS, the objectives, the case study areas, and the datasets used in this study. Chapter 2 describes the development of a GBRS method to clarify the effect of metals on the vegetation reflectance at various wavelengths from the visible to short-wave infrared (SWIR) regions. For this clarification, laboratory experiments were undertaken to investigate the relationship between the metal contents (Cu, Pb, Zn, and Cd) in soils and the reflectance spectra of a selected plant species. Then, I proposed a new vegetation index (VI) using the reflectance data at five bands from the visible green to SWIR regions, termed a vegetation index considering greenness and shortwave infrared (VIGS), for accurate detection of the vegetation stress caused by metal contamination of the soil. The results clarified the featured changes in the reflectance spectra depending upon the metal type and contents in the soil in the visible to SWIR range and moreover, the capability of VIGS to enhance the small difference in the vegetation stress due to the metal content of the soil.

The vegetation reflectance patterns in natural conditions using a multispectral remote sensing image were correlated with the geochemical concentration data (Cu, Pb, Zn, Co, Ni, Mn, Li, K, Fe, and Cr) in Chapter 3. The study area for this analysis is located in Jambi, central Sumatra, Indonesia, in which mineral deposits of porphyry copper type and mineralized zones are distributed throughout the tropical forest region. This chapter demonstrated that the reflectance values derived from one scene of Landsat 7 ETM+ imagery can be used to detect geochemically enriched zones, which probably induce vegetation stress, in dense vegetation areas.

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In Chapter 4, a new method is proposed to detect and extract the vegetation anomaly zones using the VI values by VIGS and the same data of the previous chapter. Apart from a pixel-by-pixel analysis, this chapter examines the positional concordance of the VI anomalies derived from the ETM+ image and a geostatistical technique with the concentration distributions of the selected metals (Cu, Pb, and Zn). The effectiveness of VIGS was proven because the VIGS anomalies appeared in the high-content zones common to the three metals. This trend is similar to the laboratory experiment results. Moreover, this study also demonstrates that understanding of relationship between the physical properties such as topography and the vegetation characteristics is indispensable to GBRS-based mineral exploration.

Chapter 5 presents a novel combination of remotely detected vegetation anomalies, which can be used as indicators of ore deposit occurrences, with VI values related to the physiological activities of plants. The Hokuroku district in Akita, northern Japan, was selected for this case study area. This area is one of the richest districts in Japan of the volcanogenic massive sulfide and vein type deposits and covered by thick vegetation. Superiority of the proposed method was demonstrated by the positional concordance of the vegetation anomaly zones with the high potential deposit zones derived by the geologic exploration datasets. As the result, the extracted vegetation anomaly zones were distributed along the ring structures that controlled the generation of ore deposits, and most major ore deposits located in the forest areas were found to be agreeable with the vegetation anomalies.

Chapter 6 was aimed to improve a method using directed principal component analysis (DPCA) and to extract the hydrothermal alteration zones in vegetated areas using the method by optimizing the band combination ratio and integrating it with a geographic information system-based analysis. As a case study, the Pongkor district in West Java, Indonesia was selected because the vein-type Au-Ag epithermal deposits mostly covered by thick vegetation were distributed. An ASTER imagery was used for this analysis due to its higher capability to discriminate silicates and clay minerals than Landsat ETM+ imagery through six band data in the SWIR region. The number of band of ETM+ sensor is just two in the region. This chapter clarified the best band combination and high potential deposit zones by decomposing vegetation and minerals and identifying mineral type.

Finally, Chapter 7 summarized the essential results of each chapter as a grand conclusion of this study. A list of important future works is also discussed in this chapter to develop furthermore GBRS studies for mineral exploration.

氏　名	Arie Naftali Hawu Hede

（論文審査の結果の要旨）

持続可能な社会作りや技術革新のために，金属資源の需要は年々増加しており，既開発鉱山周辺における鉱床の広がり，および経済的価値の高い新規の金属鉱床の探査・開発がますます重要な課題となっている。地球観測衛星を利用したリモートセンシングは，金属鉱床の概査法として広く適用されてきた。しかしながら，地表が植生に覆われていない乾燥・半乾燥地域が従来の適用対象となり，湿潤温暖帯や熱帯という植生に厚く覆われた地域に対しての鉱物資源探査には実用化されていない。この問題に対して，本論文は鉱床起源で，地表浅部に濃集する金属成分による植物ストレスを反射スペクトルから特定するための指標を提案したとともに，その応用によって衛星画像から植生異常部を抽出し，これが鉱床分布と整合することを明らかにできた初めての地植物リモートセンシング的研究である。以下に得られた成果の概要をまとめる。

1) 植生の生理的活性度に関する従来の指標の殆どは，クロロフィルによる電磁波吸収と葉の細胞の体積散乱にそれぞれ関連する可視域赤，近赤外域での反射率のみを用いている。その代表が NDVI（Normalized Difference Vegetation Index）である。植物ストレスは葉の水分量や変色にも現れ，この現象はそれぞれ短波長赤外域と可視域緑の反射率を変化させる。これらの性質を考慮して新しい植生指標 VIGS（Vegetation Index considering Greenness and Shortwave infrared）を考案した。Cu，Pb，Zn，Cd 溶液を土壌に含ませたコマツナの室内培養実験により，VIGS は NDVI よりも金属濃度の高低による植物ストレスの強弱を正確に表現できることを実証した。

2) 衛星画像の各画素での VIGS 値から植生異常部を抽出するために，地球統計学による VIGS 値の平滑化とトレンド成分の除去後に，ヒストグラムの閾値処理から残差を適切にクラス分けすることを試みた。この手法をスマトラ島中央の斑岩銅鉱床域と秋田県北鹿地域の黒鉱鉱床域を覆う Landsat ETM+画像に適用した結果，植生異常クラスは前者の対象域では土壌中の Cu，Pb，Zn の高濃度部，後者では既知鉱床の位置と概ね対応することを明らかにできた。また，後者のような植生の季節変化が大きい地域に対しては，季節が異なる複数の衛星画像による VIGS 値を用い，その（比／標準編偏差）が植生異常部抽出に有効であることがわかった。

3) 各画素で植物と表土の反射率が混在するような半植生の鉱床域では，代表的な鉱床関連鉱物の反射率指標と植生指標に主成分分析を適用し，植生反射率の影響を軽減させることによって，鉱床に起因した粘土化帯と変質帯を抽出できることがわかった。

以上，本論文で提案された地植物リモートセンシング法の有用性と汎用性は高く，植物ストレスの高精度抽出により，リモートセンシング鉱物資源探査を高植被率域まで拡張し得る可能性を実証した研究として，学術上，実際上寄与するところが少なくない。よって，本論文は博士（工学）の学位論文として価値あるものと認める。また，平成 27 年 12 月 16 日，論文内容とそれに関連した事項について試問を行い，申請者が博士後期課程学位取得基準を満たしていることを確認し，合格と認めた。

氏　名	Arie Naftali Hawu Hede

なお,本論文は,京都大学学位規程第14条第2項に該当するものと判断し,公表に際しては,（平成３０年３月３１日までの間）当該論文の全文に代えてその内容を要約したものとすることを認める。